A NEW APPROACH TO THE PRODUCTION OF FLY ASH BASED STRUCTURAL MATERIALS

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INTRODUCTION

Fly ash, a major by-product from the combustion of pulverized coal, has become a problem of substantial proportion at coal burning power plants. The distribution and magnitude of fly ash production in 1962 is illustrated in Figure 1. During that year fly ash production exceeded 12 million tons. It is estimated that by 1980 approximately 28 million tons of fly ash will be produced annually.[1] At present, the major portion of fly ash is dumped in a slurry in rapidly dwindling storage areas while in other locations fly ash may be sold for as much as $4.00 per ton or carried away at a cost to the power plant of as much as $2.00 per ton. Major commercial uses for fly ash today are soil stabilization in which the fly ash is utilized as a grout; asphalt paving mixes in which the fly ash acts as a filler; and light-weight aggregate in which the fly ash is pelletized and then sintered.[2]

As one facet of many involved in a United States Department of Interior, Office of Coal Research contract for the investigation of coal-associated minerals, work was initiated by West Virginia University's Coal Research Bureau with the objective of utilizing fly ash to reduce the disposal problem at power plants attributable to the lack of adequate markets. The use of a mixture of fly ash and sodium silicate as a means to make structures is documented in previous literature.[3] Early attempts to process a fly ash-sodium silicate mix experienced difficulty because the material set too rapidly for handling, produced blocks with cracks, and gave low compressive strengths. Because of these difficulties a new approach to the production of fly ash-based structural materials was sought which involves in part the use of sand in the fly ash-sodium silicate mix as an agent to increase workability and to decrease fissuring by providing a path for moisture release. Therefore, the objective of this paper is to introduce a method for using a combination of low cost materials in conjunction with modest forming pressures to produce a superior structural product which may be technically feasible. The initial phases of this work have given encouraging results and the United States Department of Interior has recently filed a patent application covering this disclosure.

MATERIALS AND EXPERIMENTAL WORK

The origin and screen analysis of fly ash used in these experiments are given in Table 1. Chemical composition of fly ash is provided in Table 2. Admixed Ohio River sand used to reduce fissuring was screened to pass 28 mesh size. Sodium silicate solution was obtained from the Philadelphia Quartz Company, the composition and properties of which are given in Table 3.

All specimens were formed by use of a floating die into the shape of a brick as a means to facilitate testing. Forming as well as breaking pressures were measured with a Baldwin Model Universal Testing Machine. For firing at high temperatures, a Hoskins electric muffle furnace was used.

In the preparation of test specimens, sand and fly ash in proper proportions were dry mixed for five minutes to insure homogeneity. This mixture was then transferred to vessels where sodium silicate was added in small increments and mixed to form pellets. A quantity of pellets was chosen which would yield a desired brick thickness when formed in the die at a specified pressure.

Generally 400 gram pellet charges were used in order to produce a 2 X 4 X 1-5/8 inch brick test specimen formed at 1000 pounds per square inch pressure (p.s.i.). Cored test specimens were two and later three 1/2 inch diameter holes were adopted as a means to increase surface area, drying, and structural strength.

The newly formed test specimens were subsequently air-dried. Next, compressive breaking strength tests were run on the air-dried bricks or on bricks which were air-dried and then fired at 1100^oC.

The final firing temperature of 1100^oC was reached through programmed temperature increases over a period of 8 to 10 hours, maintained for four to six hours, and then gradually cooled to room temperature.

Specimens were tested in accordance with the American Society of Testing and Materials (ASTM) method C67-60 entitled "Standard Methods of Sampling and Testing Brick".

RESULTS AND DISCUSSION

Five basic batch test compositions designated A,B,C,D and E and their proportions are given in Table 4. Fly ash weight percentage ranges from 64.7 to 84.5; sand from 0.0 to 22.7 and sodium silicate solution from 9.1 to 15.5.

The foregoing ranges of composition were chosen as a result of exploratory tests, some of which are not listed, which demonstrated that coarser batch compositions with less than approximately 60 percent fly ash resulted in a marked decrease in specimen strength. This observation is indicated in Table 5 with composition E (tests 16 to 24)where breaking strengths were all 4150 p.s.i. or less. On the other hand, finer batch compositions with greater than approximately 72 percent fly ash showed evidence of good breaking strength, 5060 p.s.i. or more, when air-dried for ten days (See tests 13 and 15, Table 5). However, when these batches were fired, uniform moisture release was obstructed because of their fine consistency which caused fissures and decrepitation. Also, fine compositions tended to be initially unworkable and rapidly hardened in thin superficial layers.

It is apparent from these tests that increased compressive breaking strengths resulted for specimens that could be fired. It would appear that the stronger bricks obtained by firing resulted from a solution reaction whereby the specimen underwent partial vitrification.

Results also indicate that for superior breaking strengths above 5100 p.s.i., less binder is required when using the concentrated RU (See tests 1 to 4) in place of the dilute N-type sodium silicate (See tests 5 to 24) solution. Specimens where the RU-type binder was used with modest pressure (1080 p.s.i.) gave peak breaking strengths when fired (See test 1) and superior breaking strengths when unfired (See test 4). Low (790 p.s.i.) forming pressures also yielded superior breaking strengths when fired (See tests 2 and 3).

Within the limited scope of data, variations in breaking strengths due to different fly ash composition did not appear to be significant. Thus, tests 2 and 3 which were prepared under the same conditions using high silica, high alumina Appalachian and lower silica, lower alumina Willow Island Power Plant fly ash yielded essentially the same breaking strengths (5225 versus 5150 p.s.i.).

Because of the exploratory nature of this initial test work, the effect of the number of cores, forming pressure, water addition and bulk density on breaking strengths is not indicated. The correlation of these factors is currently being investigated over more confined ranges of variation than those presented in Table V.

Additional observations indicate that the bulk density of raw fly ash in compositions A,B, and C for varying test conditions were not significantly different, ranging from 104 to 107 pounds per cubic foot. However, when portions of iron were removed from raw fly ash by magnetic separation, the bulk density of composition B decreased to 96 to 98 pounds per cubic foot. This desirable reduction in bulk density is more than likely accompanied by a decrease in breaking strengths. There is also some reason to believe, based on observations made during testing, that the reduction of iron content in fly ash is accompanied by a favorable increase in workability and a decrease in binder consumption.

In order to examine individual requirements other than physical strength, ASTM tests were undertaken on several typical specimens produced from composition B.[4] Five hour boiling tests were conducted and in no instance did the water absorbed exceed 12 percent of the original weight as compared to a permissible 17 percent for optimum grade SW brick and 22 percent for high grade MW brick. The saturation coefficient was found to be 0.79. This compares favorably with an allowable 0.78 and 0.88 in grades SW and MW bricks respectively. Additional firing shrinkage tests were also conducted and in no case did the shrinkage exceed 1/64-inch for a 4-inch test specimen (0.39% shrinkage). This is well within the allowance of standard ASTM specifications. A severe test to determine the durability of the specimens was designed and undertaken. For a period of 24 hours specimens were alternated between a steam chamber (98°C) and a freezer (-25°C) at hourly intervals in order to test their resistance to thermal and moisture decomposition under extreme temperature change. The specimens were tested while still cold and the compressive breaking strengths were found to be comparable to other test specimens of the same compositions which did not undergo the repeated freezing and heating. No such thermal gradient (123°C) exists in nature over a short period of time, the purpose of this test being only to demonstrate the durability of the specimens.

Since fly ash-based structures may, among other applications, find use as a building material some comparisons are in order. The breaking strengths of the fly ash-based test specimens compare favorably with those of common face, clay based, brick. The measured breaking strengths of six specially prepared common face bricks of dimensions similar to those of the fly ash-based test specimens exceeded approximately 2600 p.s.i. Thus, seventy-five percent of the fired and 58 percent of the unfired fly ash-based test specimens exceeded the minimum breaking strength (2600 p.s.i.) of the common faced brick. The favorable similarities in strength are further enhanced when comparing the relative bulk densities. Bulk density of the best grade pressed brick is approximately 150 pounds per cubic foot while common brick has a bulk density of 125 pounds per cubic foot.[5,6] The highest bulk density obtained from the fly ash-based test specimens did not exceed 107 pounds per cubic foot and indications are that by the removal of magnetic material the bulk density can be further reduced to less than one hundred pounds per cubic foot.

In the absence of scale-up information, a complete cost estimate for the production of fly ash-based structural products is not possible at this time. However, on the basis of information obtained from both inquiries and published sources it is possible to estimate the cost of material.[7,8,9,10,11,12,13,14] At typical prices of $1.00 per ton of fly ash, $2.29 per ton of screened sand, and $2.30 per CWT of RU-type sodium silicate, the cost of materials per thousand fly ash-based bricks amounts to $11.30. This estimate is based on brick bulk densities of 105 pounds per cubic foot for the fired test specimen of composition A. Thus, $43.70 per thousand bricks is available for costs of amortization, depreciation, labor, plant operating cost and profit from the $55.00 per thousand realization value obtainable from the sale of bricks. Work is currently directed at obtaining more detailed information on the factors which affect breaking strength and bulk density of the bricks. Such factors as materials handling, involving the effect of water additions and mixing time; forming pressure; drying time; firing rates; and firing temperature are critical and a series of factorial design experiments are currently underway.

CONCLUSIONS

Study of test results shows that the fired test specimens of composition A compare well with ASTM specifications on specimens tested. The acquisition cost of fly ash-based structural material is attractive in that cost is low for the material and long distance transportation is not involved (See Figure 1).

No definite conclusions can be drawn concerning the relationship existing between the effect of water addition, forming pressure, drying rate, and bulk density on breaking strength. The relationship between the number of coring holes and drying rate has not been determined.

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Table 1
Fly Ash and Screen Analysis

Percentage Retained of Given Mesh Size

Source	Designation	80	100	150	200	270	325	-325
Monongahela Power Company Willow Island Station	Willow Island	0.45	0.40	2.11	3.90	7.70	5.00	80.14
Appalachian Power Company Kanawha River Plant Glasgow, West Virginia	Appalachian (Electric)	0.12	0.01	0.07	0.12	0.24	3.02	95.42

Table 2
Spectrochemical Analysis of Fly Ash (%)

Designation	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Na_2O	Carbon
Willow Island	50.1	22.4	18.5	1.3	1.9	1.0	1.0	1.0
Appalachian (Electric)	58.1	27.5	6.0	1.7	1.6	1.0	1.0	2.5

Table 3
Composition and Properties of Sodium Silicate Solution

Type	$Na_2O:SiO_2$	$\%Na_2O$	$\%SiO_2$	$\%H_2O$	Specific Gravity	^oBaume 68^oF	Viscosity (Poises-20^oC)	lbs/Gal.
N	1:3.22	8.9	28.7	62.4	1.394	41.0	1.8	11.6
RU	1:2.40	13.85	33.2	53.0	1.559	52.0	21.0	13.0

Table 4
Percentage Composition of Fly Ash-Sand-Sodium Silicate Mixtures

Composition	Fly Ash (% Weight)	Sand (% Weight)	Sodium Silicate Solution (% Weight)	Sodium Silicate (Type)
A	68.2	22.7	9.1	RU
B	65.8	21.9	12.3	N
C	84.5	0.0	15.5	N
D	74.0	13.0	13.0	N
E	64.7	21.6	13.7	N

Table 5
Compilation of Test Results in Order of Decreasing Breaking Strengths According to Composition

Test Number	Composition[1]	Breaking Strength[2]	Bulk Density[3]	Method of Hardening[4]	Number Cores[5]	Forming Pressures[6]	Water Addition[7]
1.	A-WI	9190	105-107	F	3	1080	60
2.	A-WI	5225		F	3	790	60
3.	A-AP	5150		F	3	790	60
4.	A-WI	5100	105-107	10 AD	3	1080	60
5.	B-WI	6780	104-106	F	2	1080	0
6.	B-WI-IR	5400	96-98	F	3	1080	0
7.	B-WI	5260		F	2	790	0
8.	B-WI-IR	4500		F	3	1080	0
9.	B-WI-IR	3590	96-98	7 AD	3	1080	0
10.	B-WI	3560	104-106	7 AD	2	1080	0
11.	B-AP	3520		7 AD	2	790	0
12.	B-WI-IR	2800		7 AD	3	790	0
13.	C-WI	5570	104-106	10 AD	3	1080	0
14.	C-AP	1500		7 AD	2	790	0
15.	D-AP	5060		10 AD	3	790	0
16.	E-AP	4150		F	3	790	0
17.	E-AP	3200		F	2	790.	0
18.	E-WI	2460		F	2	1370	100
19.	E-Wi	2440		F	2	1900	100

Table 5 (Continued)

Test Number	Composition[1]	Breaking Strength[2]	Bulk Density[3]	Method of Hardening[4]	Number Cores[5]	Forming Pressures[6]	Water Addition[7]
20.	E-WI	1900		F	2	960	100
21.	E-AP	1525		10 AD	2	530	0
22.	E-AP	1400		21 AD	2	790	0
23.	E-AP	1220		7 AD	2	790	0
24.	E-AP	1260		7 AD	2	530	0

1. WI = Willow Island Power Plant Fly Ash
   AP = Appalachian Power Plant Fly Ash
   IR = Iron reduced by magnetic separation to approximately 5.6 percent.

2. Breaking strength in pounds per square inch (p.s.i.).

3. Bulk density in pounds per cubic foot.

4. F = Fired at 1100°C
   10 AD = Air-dried for ten days
   7 AD = Air dried for seven days

5. Number of evenly spaced holes of 1/2- inch diameter in test specimen.

6. Forming pressure in pounds per square inch (p.s.i.).

7. Water addition in milliliters.

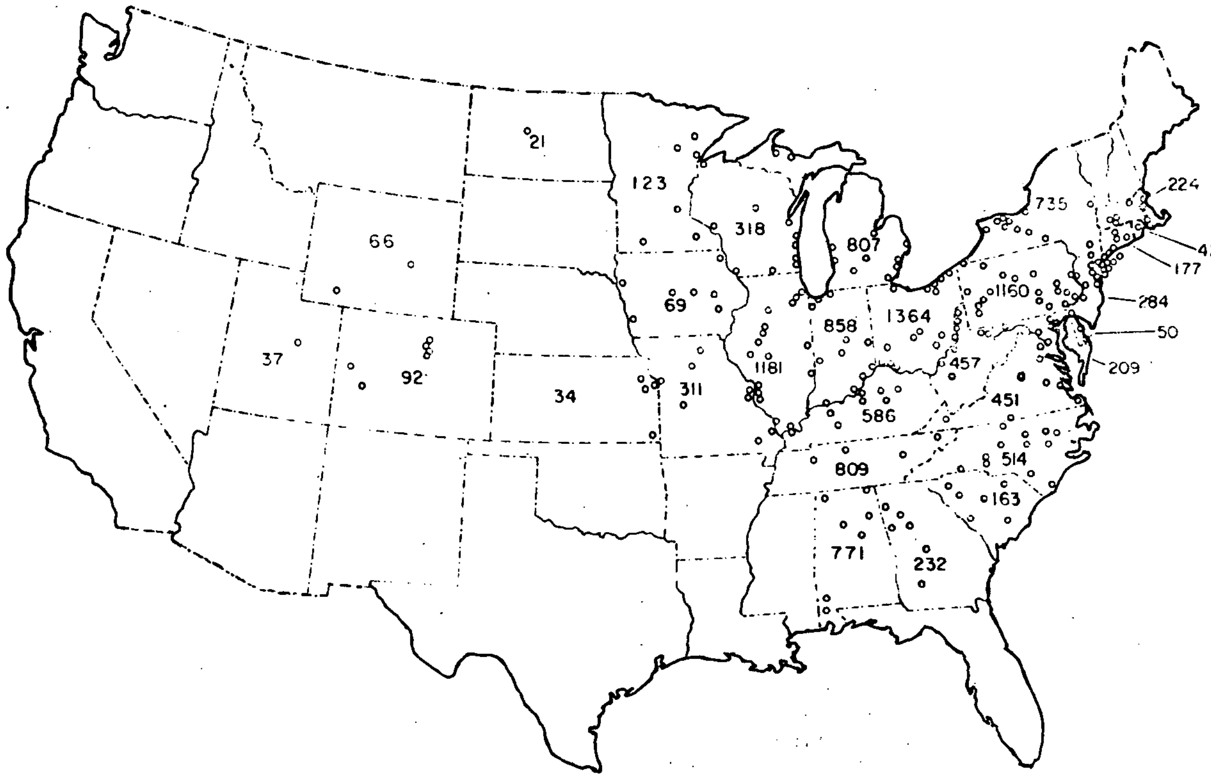

FIGURE 1
Location of Pulverized Coal Units and Fly Ash Production of Individual States (in thousands of tons)
1962